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Simplification and adjustment of the energy consumption indices of office building envelopes in response to climate change

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HIGHLIGHTS

- Taiwanese building energy conservation index (ENVLOAD) was converted to OTTV.
- New models for energy efficient envelope were proposed as an adaption to the changing climate.
- Coefficients of the OTTV model should be changed to reflect climate change.
- Thermal insulation is gaining more concern while climate change proceeds.
- Altering method of OTTV and setting new criteria in response to future climate was proposed.

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ABSTRACT

Changes in the climate system affect a building's energy consumption. Many countries have implemented building energy consumption indices to regulate the newly built buildings from excessive energy use. However, those indices were developed based on previous climate datasets and were incapable of responding to the changing climate. To stabilize the energy uses of future buildings as those under today's climate, regular updates of the evaluation index are mandatory to take climatic variations into consideration. This study firstly discussed the limitations in responding to future climate of current practicing building envelope energy conservation index in Taiwan. Secondly, we proposed a new index, the overall thermal transfer value (OTTV), based on the simulation results and tried to convert existing baseline criteria for the new OTTV. An approach on how to alter the OTTV index in response to the climate change was proposed. We found that because of the warming climate, the coefficient of the OTTV equation has to be changed over times to accurately respond to the changing climate. The approach presented in this paper provides a method on how to formulate a climate responsive index in pursuit of a better energy efficient building in the future.

1. Introduction

Given the growing awareness on the balance between the use of natural resources and the protection of the environment, the importance of building envelope design, as it relates to a building's energy performance, is increasing gradually. Many countries had adopted certain building envelope indices to regulate the building envelope design to prevent excessive energy use. The evaluation equation and the baseline value of a building's envelope thermal performance are often determined based on past climatic conditions, which are insufficient in response to the fast-changing climate in recent decades. Furthermore, none of these indices had adopted a certain mechanism on how to adapt to the changing climate, which we believe may be inappropriate in perspective of future climate responses. Due to the fact that the criteria and the assessing equations of these indices remain unchanged, it would result in the criterion complied buildings nowadays or in the future may consume more energy than those in the previous days, which is considered ineffective in perspective of controlling the building cooling energy usage. An effective index should be capable of regulating the building cooling energy use under a specific amount regardless of the changing climate at all times.

If the climate maintains the same conditions as in the past and does not change, then it will not be a problem to continue using the existing evaluation equation and baseline. However, the climate has been

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Nomenclature

A_w	areas of the external walls for air-conditioned zones, m^2
A'_w	areas of the external walls for non-air-conditioned zones, m^2
A_f	areas of fenestrations for air-conditioned zones, m^2
A'_f	areas of fenestrations for non-air-conditioned zones, m^2
A_p	total floor area of the air-conditioned perimeter zone, m^2
A_o	total area of the overall elevated building facade, m^2
CF	the correction factor of the orientation
DH	annual cooling degree-hours based on 23 °C, °C h
G	annual internal cooling load, Wh/m^2 yr
IH_i	annual total solar insolation hours of i orientation, Wh/m^2
L	heat loss coefficient of building envelope, W/m^2 K
M_i	solar insolation heat gain coefficient of i orientation of the building envelope, dimensionless
U_w	thermal transmittances of external walls, W/m^2 K
U_f	thermal transmittances of external windows, W/m^2 K
K_i	external sunshade shading coefficient of i orientation
S	the heat storage capacity of walls
SC	the shading coefficient of fenestrations, dimensionless
SC_1	the glass shading coefficient, dimensionless
SC_2	the external sunshade shading coefficient, dimensionless
SF	the annual average solar radiation factor for the specific reference orientation, W/m^2
Tu	the average room temperature increment, °C
TD	the average temperature difference between the indoor and outdoor air, °C
TD_{eq}	the average equivalent temperature difference of external walls during the cooling seasons, °C
a_0, a_1, a_2	constant coefficients of the ENVLOAD
b_0, b_1	constant coefficients of the simplified ENVLOAD
c_1, c_2, c_3	constant coefficients of the OTTV

Subscript letters

i	i orientation of the building envelope
w	walls
f	fenestrations
p	parameter zones
o	overall area
eq	equivalent temperature

Greek letters

η	solar heat gain coefficient (SHGC)
δ_1	thickness of the insulation material in wall, cm
δ_2	thickness of the heat storage material in wall, cm
θ	azimuth angle

Acronyms

ENVLOAD	annual building envelope sensible cooling load, kWh/m^2 yr
$ENVLOAD_{simple}$	simplified calculation equation of ENVLOAD, kWh/m^2 yr
IA	index of agreement
MB	mean bias
OTTV	the overall thermal transfer value
RMSE	root mean square error
SCL	annual sensible cooling load
SHGC	solar heat gain coefficient of the glazing
SRC	standardized regression coefficient
WWR	window to wall ratio

changing under accelerating speeds in recent decades and will be in a state of continuous change. Therefore, facing the challenges of future climate change, a conceptual leap in building thermal performance design will be necessary; particularly, the present evaluation method and the baseline value of a building's thermal performance should be constantly updated over times by a new model, taking consideration of the differences in the present and future climatic states. In other words, it is an important issue that also must be further studied in depth by using existing future climate data and by carefully amending the provisions on the thermal performance of building envelopes, to guide the new direction of building energy conservation design in facing with the changing climate.

1.1. The Taiwanese thermal performance evaluation index (ENVLOAD)

During the 80s of last century, Taiwan promulgated the Building Energy Conservation Design Standard. The standard provides a performance-based approach to guide the energy conservation design of building envelopes. The performance-based approach comprehensively considers the three main parts of energy consumption of a building envelope: conduction heat through opaque external walls, conduction and solar radiation heat through window fenestrations. The standard also allows trade-offs in between them, providing innovation and flexibility in building design for architectural designers. The focal point of the performance-based approach is expected to reduce building energy consumption through good envelope design; it focuses on the long-term or annual total energy consumption of the building's envelope. The thermal performance evaluation index of the office building, according to the standard, is called the ENVLOAD. The ENVLOAD represents the annual sensible cooling load in an air-conditioned building perimeter zone of a unit square meter floor area during the cooling season. The perimeter zone refers to the indoor space within a distance of 5 m from the external wall, where it is susceptible to heat flow through the building envelope. The calculation of ENVLOAD [1] is as follows:

$$ENVLOAD = -20370 + 2.010G + 0.033L{\cdot}DH + 1.079\sum_i (M_i{\cdot}IH_i) \tag{1}$$

$$G = 13.5(a_0 + a_1 T_u + a_2 T_u^2) \tag{2}$$

$$T_u = \frac{13.5}{L} \tag{3}$$

$$L = \frac{\sum_i (U_{w,i}A_{w,i}) + 0.5\sum_i (U_{w,i}A'_{w,i})}{A_p} + \frac{\sum_i (U_{f,i}A_{f,i}) + 0.5\sum_i (U_{f,i}A'_{f,i})}{A_p} + 1.011 \tag{4}$$

$$M = \frac{\sum_i (K_i\eta_i A_{f,i}) + 0.5\sum_i (K_i\eta_i A'_{f,i})}{A_p} + \frac{0.035[\sum_i (U_{w,i}A_{w,i}) + 0.5\sum_i (U_{w,i}A'_{w,i})]}{A_p} \tag{5}$$

Since there are many variables contained in Eqs. (1)–(5) and there are many combination types of various variables, the calculation process and the lookup of tables tend to be overly complicated and cumbersome. In view of this, Wang and Lin [2] proposed a simplified calculation equation (hereinafter referred to as $ENVLOAD_{simple}$), as shown in Eq. (6):

$$ENVLOAD_{simple} = b_1\left[\frac{\sum_i (K_i\eta_i A_{f,i} IH_i)}{A_o}\right] + b_0 \quad (6)$$

ENVLOAD index was adopted as a Taiwanese building envelope index in the 90s. Since then, except that Wang [3] simplified the ENVLOAD index for office buildings in 2005 and Lai [4] proposed a correction term on the ENVLOAD for the application of naturally ventilated office buildings in 2008, there is no further review or revision made to the ENVLOAD index. A recent study conducted by Shih et al. [5] demonstrated that the assessment is convertible between the indices of ENVLOAD and the OTTV, which the latter is commonly adopted by many Southeast Asia countries.

1.2. The overall thermal transfer value (OTTV) index

Similar to ENVLOAD, OTTVis also a thermal performance index of a performance-based building envelope. The OTTV is an index that estimates the rate of average heat-transfer through the building envelope [6]. It was proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) in 1975 [7] and, at present, has been widely adopted by many countries and cities, particularly those in Southeast Asian countries having the same hot and humid climate as Taiwan, like Singapore [8,9], the Philippines [10], Thailand [11], Malaysia [12], Indonesia [13], and Hong Kong [14–16]. All these countries have established the OTTV standards during the 80s and 90s of the last century as a part of building energy standards. The meaning of OTTV is the total amount of heat transfer in terms of the conduction heat through opaque external walls (Q_w), the conduction heat through fenestrations (Q_f), and the solar radiation heat through fenestrations (Q_s) per square meter of the building envelope. The calculation is shown in Eq. (7):

$$\begin{aligned} OTTV_i &= \frac{Q_w + Q_f + Q_s}{A_i} \\ &= \frac{A_w \cdot U_w \cdot TD_{eq} + A_f \cdot U_f \cdot TD + A_f \cdot SF \cdot CF \cdot SC}{A_i} \\ &= (1-WWR)\cdot TD_{eq}\cdot U_w + WWR\cdot TD\cdot U_f + WWR\cdot SC\cdot SF\cdot CF \end{aligned} \quad (7)$$

where the SC is the shading coefficient of fenestrations, which is the multiplication between the glass shading coefficient (SC_1) and the external sunshade shading coefficient (SC_2). The solar heat gain coefficient of glass (η) is generally 0.86 times the shading coefficient of glass, *i.e.* $\eta = 0.86{\cdot}SC_1$. The three meteorological variables, TD_{eq}, TD, and SF, associated with Eq. (7) are usually obtained by referring to long-term meteorological data over many years and by calculating the averages. Generally, TD_{eq}, TD, and SF are fixed numerical values for a city or a region. If these fixed values are replaced by constant coefficients, OTTV can be expressed as:

$$OTTV_i = c_1\cdot(1-WWR)\cdot U_w + c_2\cdot WWR\cdot U_f + c_3\cdot WWR\cdot SC\cdot CF \quad (8)$$

The OTTV of entire building external walls ($OTTV_w$) is an area-weighted average of the OTTV of external walls ($A_{w,i}$) at different orientations i, as shown in Eq. (9):

$$OTTV_w = \frac{\sum OTTV_i \times A_{w,i}}{\sum A_{w,i}} \quad (9)$$

Although OTTV is merely an index for evaluating building envelope's energy performance, many attempts have been made to correlate the OTTV to the building energy consumption. Chua and Chou [17] investigate the impact the wall absorptance has on OTTV and incorporated the wall absorptance to calibrate the OTTV. They also performed a relative ranking on the functional parameters of OTTV to evaluate their effectiveness in lowering the OTTV of buildings, which is a part of an effort in a program to develop a scheme for rating energy and carbon performance of residential buildings. Tummu et al. [18] present the development of OTTV formulation for the bedroom of a residential building, which is a part of an attempt to develop a building energy performance measures for residential buildings in Thailand. Singhpoo et al. [19] found relationships to predict the OTTV at different times in one day to determine the impact of equivalent temperature difference for opaque walls, and temperature difference for glass windows in order to further adopt OTTV as an index to improve the energy consumption efficiency in buildings. Chan and Chow [20] reported the details of the methodology and findings of deriving a dataset of correction factors which can be used by architects and building engineers to calculate the OTTV of air-conditioned commercial buildings constructed with naturally ventilated double skin façade, while in another article [21] they reported the correction factors that can be used to compute the OTTV of a building constructed with green roof. As the ambient temperature continues to rise due to global warming, Wong et al. [22] revealed that the design of residential buildings in Singapore might be affected, and suggested the current Singaporean OTTV regulations may have to be revised in the future.

By reviewing the existing literature, the OTTV related researches focused on how to modify the OTTV to improve the prediction accuracy of annual cooling or heating load. One common deficiency is that these modified OTTVs were still developed based on simulations using meteorological data of the past. As OTTV is meant to regulate the thermal performance of new buildings, using an antiquated-climate based index may guide architects doing thermal performance design of a new building while facing with historical weather. However, future climate is the weather condition a newly built building is actually facing with instead of the climate of the past. A building that is complied with the past climate is not necessarily guaranteed to suffice future energy consumption requirement. It will not be a problem if the magnitude of climate variation is not evident. However, the changing of the climate is significant in recent years. Moreover, favored from the advancement of construction techniques, it adds the fact that the lifespan of newly built buildings will extend longer than in the past, resulting in new buildings are more susceptible to the future climate. Therefore, it is imperative to develop and formulate a new OTTV based on future climate.

1.3. Objectives of the study

The building envelope design in subtropical climates has a significant influence on the cooling demand, so the thermal performance index and its baseline value of the envelope play important roles. A suitable thermal performance index must be able to alert architects' awareness and concern on building energy conservation design and be able to accurately reflect the actual energy use efficiency of buildings. Simultaneously, as a basis for guiding the national building energy efficiency policy, the proposed building thermal performance index must be of a user-friendly interface. Taiwan's building energy conservation regulations have been implemented for nearly 20 years, and now the government is prepared to review it, which is a good timing to re-examine the ENVLOAD.

ENVLOAD and OTTV are equally performance-based indices. Both take consideration of the necessary six variables for the thermal performance indices of envelopes: window-to-wall ratio, external wall U value, glass U value, glass shading coefficient, external sunshade shading coefficient, and solar radiation orientation correction. Chan and Chow [23] surveyed existing commercial buildings in Hong Kong and demonstrated that there is a very high correlation between the predicted OTTV and the chiller-load demand. They claimed that using OTTV index is an effective measure to ensure an energy-effective design of building envelope, and can be a practically enforceable item of legislation for building energy control. Thus, this triggers the first study objective of this paper: Can OTTV be used as an alternative index to simplify the ENVLOAD? On the other hand, a building structure often possesses a service lifespan of up to 50 years or even longer. It is important to be able to analyze how a building will respond to climate change in the future and to evaluate possible changes in energy use.

Therefore, another objective of this study is to calculate the changing trends of cooling loads in the perimeter zones of office buildings in Taiwan, between the 30 years under the present climate (2005–2019) and the near future (2020–2034), through EnergyPlus simulations. A comparative analysis will be conducted on the cooling loads in the perimeter zones of buildings in these two time intervals, exploring how to revise the envelope performance index to guide energy conservation building design as a mitigation measure in response to climate change.

2. Methodology and materials

Building thermal performance indices are usually derived from the post-processing of building energy simulation results. In the past few years, in the field of building simulation study, there has been an increasing interest in using uncertainty analysis techniques. Based on the uncertainty of a building's performance evaluation and based on the possibility that it generates potential influence on design decision-making, de Wit and Augenbroe [24] elucidated how to integrate a quantitative uncertainty evaluation into the design decision-making analysis, and emphasized that using uncertainty to evaluate the thermal performance of a building is indispensable in reasonable architectural design decision-making. Macdonald and Strachan [25] illustrated the practical application of uncertainty analysis in building performance simulations by combining the review of uncertainty sources with the use of simulation software. Encinas and Herde [26] determined the most sensitive building envelope design variable influencing the summer comfort level and the net effect of every single variable by executing global and partial uncertainty analyses. In the study of Yıldız and Arsan [27], existing apartment design in the Turkish city of Izmir was taken as the subject of discussion; by conducting an uncertainty analysis, they determined the most important envelope design variable of apartment buildings in response to the hot and humid climate of the region. The study of Breesch and Janssens [28] used the results based on an uncertainty analysis and building energy simulations to develop an evaluation method to predict the performance of natural ventilation in buildings at night. Chen et al. [29] took an uncertainty analysis to interpret the relationship between input variables and output indices of a building model and provided a reliable building performance prediction. Their research also pointed out that the results obtained from the uncertainty analysis can improve the efficiency of future optimization studies. Hopfe and Hensen [30] conducted uncertainty analysis on an office building to demonstrate the added value and usefulness of integrating uncertainty analyses and building performance simulations, by elucidating the resulting influence of various building structure performance variables on energy consumption and thermal comfort levels. Taking residential buildings as a case study, Rodriguez et al.'s [31] paper emphasized executing building energy simulations using the uncertainty method, which is helpful to simplify the understanding of building performance while obtaining reliable results. Lai et al. [32] used an uncertainty method to analyze the influence of future climate change on residential air-conditioning energy consumption in Taiwan. De Wilde and Tian [33] applied the uncertainty analysis to a thermal simulation to identify key factors for prediction of overheating and energy use of office building when subject to climate change.

The study flow process of combining uncertainty analysis and building energy consumption simulations can be divided as pre-processing, simulation execution, and post-processing, and as follows:

2.1. Pre-processing – Monte Carlo analysis

One of the studies by Macdonald [34] demonstrated that the Monte Carlo analysis, in coordination with random sampling, is the best combination for typical building simulation applications. The Monte Carlo method had been used extensively to quantify the sensitivity of parameters in the field of building simulation. An early work done by Lomas and Eppel (1992) [35] analyzed three methods of conducting sensitivity analysis and evidenced that the Monte Carlo method is the preferred technique. A diverse range of building simulation applications such as Hyun et al. [36] and Kotek et al. [37] have successfully used the Monte Carlo method in parameter sensitivity studies. Therefore, the Monte Carlo analysis was adopted for all the input variables considered in this study. The whole process can be summarized by Eq. (10). In the equation, y is the output variable of a random sample. The annual sensible cooling load is selected as the output variable. N is the number of samples, k is the number of input variables, and x is the input variables generated by random sampling. Latin hypercube sampling of uniform distribution is selected and used in this study. For accuracy, 1000 simulation operations were performed.

$$\overrightarrow{Y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix} = \begin{bmatrix} f(x_{11}, x_{12}, \ldots, x_{1k}) \\ f(x_{21}, x_{22}, \ldots, x_{2k}) \\ \vdots \\ f(x_{N1}, x_{N2}, \ldots, x_{Nk}) \end{bmatrix} \tag{10}$$

This paper mainly focuses on the regression analysis of the design variables of building facade in general building models with the air conditioning in operation. According to ASHRAE Standard 90.1 [38], the northern region of Taiwan is classified as Zone 1 (hot climate zone) and the southern region is classified as Zone 2 (hot-humid climate zone). These 2 climate zones are both cooling-dominated regions. The main design strategy for building envelope in both climate zones aims to control the solar heat gains through windows with external sunshades and to use opaque external walls with good thermal insulation. The design variables provided in building energy conservation regulations are as follows: building orientation, window-to-wall ratio, external wall U value, external window U value, glazing's SHGC, and the external sunshade depth ratio. These variables also mutually coincide with the main design strategy guidelines for building envelope in cooling-dominated regions. Therefore, this paper directly generalizes these 6 variables of building orientation, window-to-wall ratio, external wall U value, external window U value, SHGC, and sunshade depth ratio, together with the heat storage capacity of the external wall, as the input variables of the building model. The variation range of these input variables must cover all possible architectural engineering practices and be uniformly distributed within its variation range. The details are shown in Table 1.

Table 1
Input variables of the building model, probability distribution, and variation range.

Input variable	Unit	Probability distribution	Range	Corresponding variables in EnergyPlus
Orientation	(degree angle)	Evenly distributed	8 orientations (N, NE, E, SE, S, SW, W, NW)	Azimuth (θ in Fig. 2(a))
Width of the perimeter zone	m	Evenly distributed	10–50 m	Width of the space (L_1-L_4 in Fig. 2(a))
Window-to-Wall ratio	(–)	Evenly distributed	0.1–0.9 m	Height of the window (h in Fig. 2(b))
U-value of the exterior wall	W/m^2K	Evenly distributed	0.5–5.0 cm	Thickness of the insulation material (δ_1 in Fig. 2(b))
S-value of the exterior wall	kJ/m^2K	Evenly distributed	2.0–153 cm	Thickness of the heat storage material (δ_2 in Fig. 2(b))
U-value of the fenestration	W/m^2K	Evenly distributed	1.0–5.5 cm	U value of the glazing
SHGC of the fenestration	(–)	Evenly distributed	0.1–0.85	SHGC of the glazing
Depth ratio of the sunshade	(–)	Evenly distributed	0.0–2.0	Depth ratio as depicted in Fig. 2(d)

2.2. Executing building energy simulation

In this study, EnergyPlus 8.6 [39], a building energy consumption simulation tool, was selected to analyze the annual sensible cooling load. This is because EnergyPlus has been widely validated, and is the most prevailing tool used for building performance simulation and optimization [40]. The second generation Canadian Earth System Model (CanESM2) was used to predict future climate change in terms of the CO_2 emission scenario under the Representative Concentration Pathway 4.5 (RCP 4.5). Similar to other general circulation models (GCM), CanESM2 provides only the monthly variations of the dry bulb temperature, diurnal temperature difference, relative humidity, wind speed, and solar radiation that can have significant influences on the heating and cooling loads of buildings. As a result, the monthly data provided by CanESM2 is not sufficient for the hourly energy simulation. Therefore, we used the morphing method [16,41,42] together with the observed hourly local meteorological data to temporally and spatially down-scale the meteorological data. In this study, the typical meteorological year 3 (TMY3) dataset [43] of Kaohsiung, obtained from the Architecture and Building Research Institute under the Ministry of the Interior, was adopted as local meteorological data. From CanESM2, the monthly data for the last 15 years (2005–2019) and the next 15 years (2020–2034) was obtained. The hourly variation was applied indiscriminately to TMY3 by using the morphing method. The resulting hourly meteorological datasets between these 30 years, from 2005 to 2034, were afterward used for EnergyPlus simulations. The detailed production process of future meteorological years in Taiwan regions can be found in Huang and Hwang's paper [44].

Fig. 1 shows the yearly variation summary of the horizontal solar radiation and the annual cooling degree-hours for the office building in cooling seasons (yearly from May to October and daily from 07:00 to 19:00) in 2005–2034. A significantly growing trend in cooling degree-hours can be observed. The annual average value between 2005 and 2018 is 14,967 degree-hours, while the annual average value between 2020 and 2034 is 16,152 degree-hours. The 1185 degree-hours rise is equivalent to a 7.9% rise rate. As for the solar radiation, there is no obvious increment from 2005 to 2034. The annual average value between 2005 and 2019 is 739 MWh/m^2, which is almost consistent with the annual average value of 746 MWh/m^2 from 2020 to 2034.

Regarding the building model, it is impossible to represent all the possible architectural shapes and geometries. However, as long as the variables selected in Table 1 can be met, it will be sufficient to understand how the building envelope design influences the fundamental demand of the annual cooling energy use. Therefore, the general office building model, as shown in Fig. 2, is selected in this paper. The typical building plan is divided into 4 air-conditioned perimeter zones, as well as an air-conditioned core space and one zone of non-air-conditioned spaces for the stairs, elevators, or washrooms. Perimeter zones refer to the indoor spaces within a distance of 5 m from the external walls; these spaces are susceptible to the heat flow exchange of the envelope. The 4 air-conditioned perimeter zones are the spaces of interest and were analyzed in this paper, whereas other zones are not in the scope of consideration for energy consumption simulation. The input variables of the building envelope are described as follows:

(1) Building orientation: The orientations of perimeter zones determine the magnitude of the incident solar radiation intensity and the length of time exposed to sunshine; it will naturally influence the annual sensible cooling load. Building orientation is commonly expressed as the azimuth angle, θ, shown in Fig. 2(a). In Taiwanese building energy conservation regulation, the building orientation is not continuous; it is divided into 16 main orientations.
(2) Length of the perimeter zone: To ensure the accuracy of using the area-weighted method for calculating the building envelope's energy consumption index, is another objective of conducting the building energy simulation. This is also the reason why the lengths of the perimeter zones at each orientation (L_1-L_4 in Fig. 2(a)) are set as independent variables in this paper, instead of adopting the aspect ratio as the variable. The variation range in lengths of the air-conditioned perimeter zone lies between 10 m and 50 m, which equivalents to the floor geometry aspect ratio of 1000 simulation cases lie between 0.2 and 5.0.
(3) Window-to-wall ratio: Fig. 2(b) illustrates the fenestration configuration assumed for each elevation. The window-to-wall ratio is defined as the ratio of the fenestration area to the total building elevation area. In this study, the window-to-wall ratio varied between 0.1 and 0.6. The height of each floor was fixed at 3 m; the window height (h) in Fig. 2(b) varied between 0.3 m and 1.8 m according to the corresponding window-to-wall ratio.
(4) Exterior wall's U value (U_w) and S value: The U value and S value determine the construction of the opaque external wall. The U value, representing the thermal insulation capability, will generate an insulation effect on the heat transmitted; the S value, representing the heat storage capacity, will affect the amount of simultaneous peak heat flux and the time-lag effect of heat conduction through exterior walls. The wall construction assumed in this study is shown in Fig. 2(c). This wall construction profile is simplified from a typical reinforced concrete external wall. The polystyrene board (PS board) is used as the thermal insulation material and the concrete layer is regarded as the heat storage material. The U value and S value of the external wall were varied by changing the thicknesses of the PS board (δ_1) and the thickness of the concrete layer (δ_2), as illustrated in Fig. 2(c). In this study, the PS board thickness varied between 7.4 cm and 0.2 cm, resulting in the external wall U value being varied between 0.5 W/m^2 K and 3.5 W/m^2 K. The concrete thickness varied between 0 cm and 31 cm, resulting in the S value being varied between 0 kJ/m^2 K and 153 kJ/m^2 K. The S value of the exterior wall is equal to the multiplication result of the three properties of thickness, specific heat, and density of the concrete layer.
(5) External window's U value (U_f) and SHGC: In this study, ASHRAE Handbook Fundamental 2016 [45] was used as a reference, which provides reference values of U_f and SHGC for commercially available glass. The variation range of the U value was between 1.5 W/m^2 K and 6.0 W/m^2 K; the range of SHGC was between 0.2 and 0.8.
(6) Depth ratio of the sunshade: The referred literature [1] and [46] point out that when the sunshade's depth ratio exceeds 2.0, the external sunshade's shading coefficient remains almost constant. In this study, the continuous horizontal sunshade attached exactly above the window is assumed; the variation range in the sunshade's depth ratio is taken as between 0.0 and 2.0. The depth ratio of the sunshade refers to the ratio of the sunshade slab's depth to the window's height, as illustrated in Fig. 2(d).

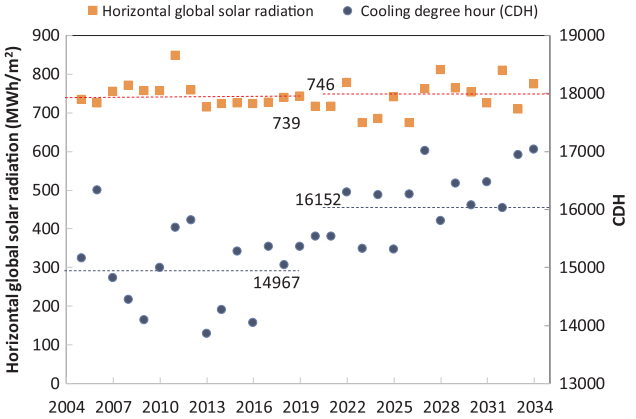

Fig. 1. Variation trends in solar radiation and cooling degree-hours during the simulation periods (2005–2034).

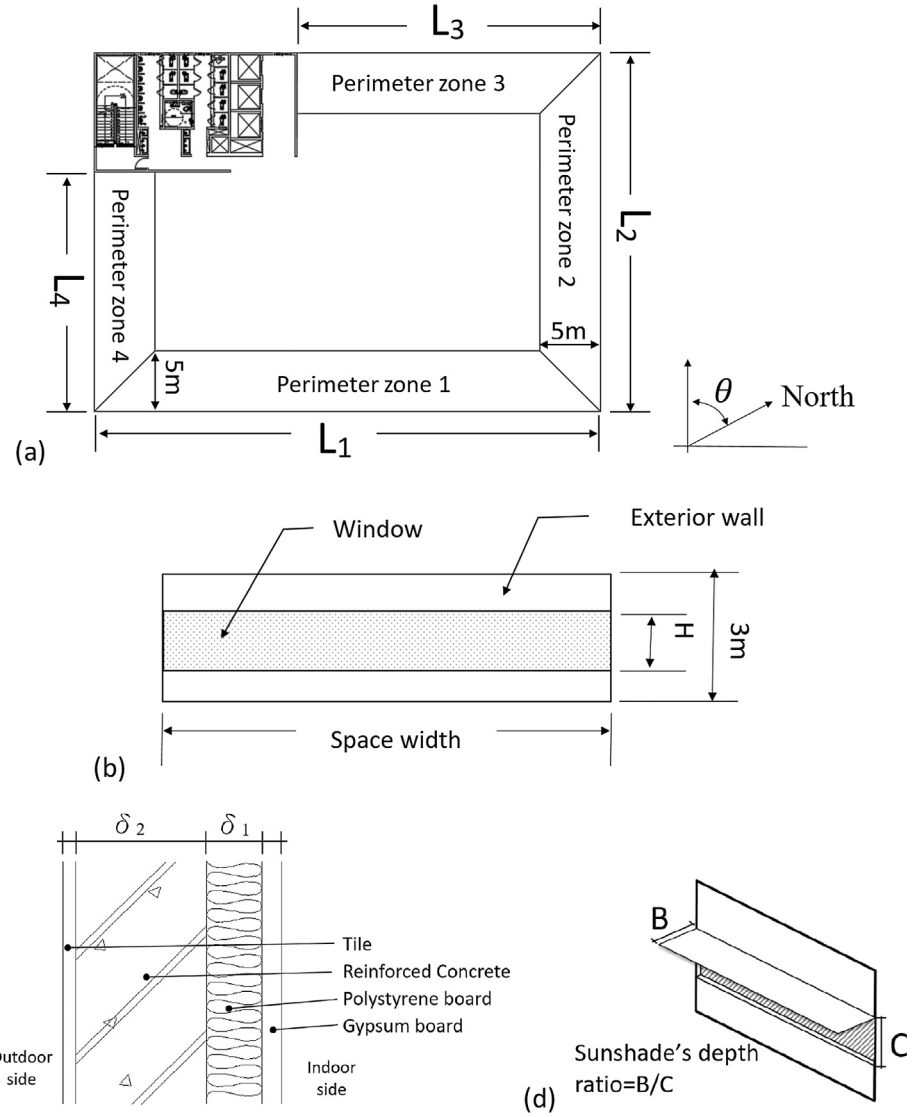

Fig. 2. Typical building model used in building energy simulations: (a) Building plan, (b) Elevation of a single floor, (c) Construction profile of external wall, and (d) Depth ratio of the horizontal sunshade.

Other variables, such as the internal load and the operation control of air-conditioning systems are not included in the modeling process so that the unique influence of the building envelope passive design's thermal performance on the annual sensible cooling load can be observed. The air conditioning system only operates on weekdays during the main cooling seasons from May 1st to September 30th, and the daily operating time period is from 07:00 to 19:00. The indoor temperature is set to 26 °C. The outdoor air supply, referring to ASHRAE Standard 62, provides 8.5 L/s per person. As regards to internal heat gain, the office occupant density is 0.15 person/m^2, lighting density is 11.8 W/m^2, and the power density of office equipment is 12.5 W/m^2. The schedules of occupancy rate, and the lighting and equipment usage rate on weekdays are determined according to ASHRAE Standard 90.1.

2.3. Post-processing – sensitivity analysis

In this study, since the pre-processing followed the Monte Carlo analysis in coordination with a simple random sampling, all the input variables were altered at the same time. Therefore, the post-processing should adopt a global sensitivity analysis to evaluate the output response and conduct the subsequent regression analysis. A sensitivity index used in this paper is the standardized regression coefficient (SRC). The standardized regression coefficient is used to measure the linear influence of each input variable on the output variable. The absolute value of the standardized regression coefficient indicates the relative importance, while the positive and negative sign indicates the changing direction of the output relative to the input.

The SRC is used to measure the magnitude of the influence in a linear fashion. However, the influences of the building orientation and the sunshade depth ratio on the annual sensible cooling load are not linear, so it is necessary to seek another alternative variable, which is able to exhibit a linear influence on the sensible cooling load. The orientation correction factor (*CF*) is defined as the ratio of the incidence on any orientation to the incidence on a certain reference orientation of the annual solar radiation. In this study, the *CF* calculation is based on the Southern direction as a reference orientation. As for the external sunshade of any fenestration on the building facade, the definition of the sunshade's correction factor (*K*) is the ratio of the annual solar radiation incidence on the external surface of the windows to the annual solar radiation without sunshade. In other words, the annual solar radiation at any orientation is linearly related to *CF* or *K*. So, during the sensitivity analysis in this study, the azimuth angle was replaced by the orientation correction factor of solar radiation; the sunshade's depth ratio was replaced by *K* as the input variable.

3. Index simplification

In this section, we will discuss how to conduct the simplification and the baseline conversion of the currently active envelope performance index according to the simulation results of the meteorological data for the years between 2005 and 2019.

3.1. Annual sensible cooling loads of 1000 cases under the current climate

For 1000 case samples, as shown in Fig. 3, the annual sensible cooling load lies between 85 kWh/m^2 and 140 kWh/m^2. There is a significant gap between the minimum and maximum values, so the combination of each building variable should be carefully taken into consideration in the early design stages to ensure good thermal performance for office buildings. Otherwise, the restrictions of the building energy conservation index should be followed to prevent buildings from excessive annual sensible cooling loads.

3.2. Sensitivity analysis

If individual input factors are independent of each other, it is appropriate to choose the SRC as an index for measuring the relative significance or sensitivity of each input variable. The relative significance of the input factor can be ranked based on the magnitude of the SRC absolute value. Based on the 2005–2019 simulation results, the SRC calculation results are sorted sequentially in descending order and summarized in Table 2. Notably, the glass shading coefficient (SC_1) has the largest value, which means that it has the most significant influence on the annual sensible cooling load. Meanwhile, the adjusted coefficient of determination (R^2) in Table 2 indicates that SC_1 accounts for more than 30% of the observed uncertainty. This is followed by the window-to-wall ratio (*WWR*) and external sunshade shading coefficient (SC_2). These three parameters, SC_1, *WWR*, and SC_2, decide the magnitude of the solar radiation heat gain through fenestrations, accounting for more than 70% of the observed uncertainty. Next are the external wall U_w value, the orientation correction factor (*CF*) value, and the window glazing's U value (U_f). Although the numerical value of SRC for U_f is lower and the relative significance seems to be very small, it has reached the threshold of statistical significance ($p\text{-value} \ll 0.01$) and therefore its influence still must be taken into consideration. For the SRC calculation of the external wall heat storage coefficient (*S*), it has not yet reached a significant level ($p\text{-value} > 0.01$). In other words, the influence/effect of the changing for the heat storage capacity of the wall's construction on the annual sensible cooling load can be ignored. Table 2 shows that excluding the wall's *S* value, the remaining six parameters in the table totally accounts for more than 80% of the observed uncertainty.

3.3. OTTV model establishment

Hui [15] revealed a general method to develop the OTTV equation. The OTTV equation is mainly determined by indiscriminately applying the multivariate regression technique into the results outputted from the vast amount of building energy simulations. Eq. (11) adopts the concept of a weighted average with the areas of the external walls at different orientations to calculate the OTTV of an entire building. Therefore, when constructing the regression equation, the OTTV models for various orientations should first be established, and then the OTTV for an entire building is obtained by the area-weighted average method. To confirm the accuracy of using the area weighted average method to obtain the entire building's OTTV, following steps were performed.

Among 1000 building simulation cases, every building case has 4 perimeter zone samples with different orientations, so there will be 4000 samples available for the multivariate regression analysis of the OTTV equation including 8 different orientations. Among the 8 orientations, each orientation has 500 samples. Table 3 lists the yearly distribution range of the multivariate regression coefficients and the R^2 for the average annual sensible cooling load over 15 years for the period from 2005 to 2019. The R^2 for multivariate regression varied between 0.95 and 0.98, indicating that the regression model is strongly robust. The building envelope thermal performance index is used to regulate the long-term energy consumption of a building envelope. We chose the multivariate regression results obtained by taking the average annual sensible cooling loads over 15 years, and constructed an appropriate OTTV calculation equation:

$$OTTV_{i,current} = 5.1(1-WWR)\cdot U_w + 1.6WWR\cdot U_f + 107.7WWR\cdot SC\cdot CF \quad (11)$$

3.4. Correlation between the thermal performance index and the annual sensible cooling load

The OTTV of all 1000 samples can be calculated using Eq. (11). Fig. 4(a) shows the relationship of the entire building's OTTV against to the building's annual sensible cooling load. For the linear regression in the plot, the R^2 is significantly as high as 0.978, indicating that using the OTTV of the entire building as a single independent variable can accurately predict the annual sensible cooling load. Fig. 4(b) and (c) also depict the relationships of ENVLOAD and $ENVLOAD_{simple}$ against the annual sensible cooling load. The ENVLOAD had an $R^2 = 0.93$, indicating that the ENVLOAD can also accurately make the prediction. Meanwhile, $ENVLOAD_{simple}$ had an $R^2 = 0.87$, which is slightly poor.

Apart from the R^2 that is used to measure the linear correlation between the predicted values and actual values, there are still the mean bias (MB), root mean square error (RMSE), and index of agreement (IA). These typical statistical indices are commonly used to describe the deviations of the predicted values from a particular model against the actual dataset. To check the prediction performance of each model, we conducted a comparison of the model predicted values and the simulation derived data from 1000 building samples, as shown in Table 4. For the correlation coefficients of the OTTV model, $R^2 = 0.980$ and IA = 0.931 were the highest, while MB = 0.88 and RMSE = 1.14 were the lowest, indicating the established OTTV model has the best prediction performance. Relatively, the simple model of $ENVLOAD_{simple}$ had the lowest R^2 (0.88) and IA (0.82), as well as the highest MB (2.08) and RMSE (2.64), indicating that it will have large prediction errors.

Summarily, OTTV and ENVLOAD both equally use multivariate regression analysis and building energy simulation tool to establish prediction equations. The ENVLOAD also uses a 3-level L81 orthogonal array to generate 81 simulation samples, which is different from the Monte Carlo in coordination with Latin hypercube sampling method used in this paper to generate 1000 simulation samples. Moreover, ENVLOAD uses earlier meteorological data (TMY), which is naturally

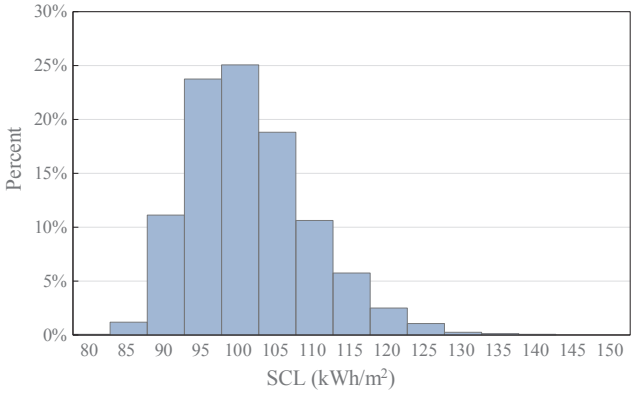

Fig. 3. Distribution frequencies of annual sensible cooling loads among 1000 samples during the period between 2005 and 2019.

Table 2
Compilation of SRC results.

Variables*	*2005–2019*				
	Range		Mean	*p-value*	Adj. R^2
SC_1	0.516	0.543	0.535	0.000	0.344
WWR	0.446	0.479	0.463	0.000	0.589
SC_2	0.375	0.399	0.390	0.000	0.737
U_w	0.167	0.203	0.183	0.000	0.775
CF	0.141	0.168	0.149	0.000	0.827
U_f	−0.002	0.054	0.023	0.006	0.827
S	0.000	0.005	0.002	0.822	0.827

* Note that the variables were sequentially added in a forward stepwise fashion.

Table 3
Multivariate Regression coefficients results of the OTTV equation.

Variables	Range	Mean
$(1\text{-}WWR)\cdot U_w$	4.6–5.8	5.1
$WWR\cdot U_f$	0.8–2.2	1.6
$WWR\cdot SC\cdot CF$	104.3–112.2	107.7
R^2		0.95

different from the TMY3 used in this paper. These are the reasons why ENVLOAD will have greater error. However, it is undeniable that Eqs. (8) and (9) are indeed easier to understand and simpler than Eqs. (1)–(6).

The reason why the $ENVLOAD_{simple}$ is less accurate is detailed as below. As described in the literature, although the $ENVLOAD_{simple}$ adopts the identical sampling method with the same variable input range as those used in developing ENVLOAD, the values of the dependent variable in the multivariate regression are the numerical values of ENVLOAD calculated according to Eqs. (1)–(5), instead of the building energy consumption simulation results derived from building simulation tool. This approach will allow the prediction model of the $ENVLOAD_{simple}$ to accumulate the existing prediction errors of ENVLOAD. Coupling with the errors generated by the $ENVLOAD_{simple}$ model itself, it is naturally not a surprise that the simple model will have poorer prediction performance. Moreover, Eq. (6) shows that $ENVLOAD_{simple}$ uses only 4 predicting variables, *i.e.* the window-to-wall ratio, glass shading coefficient, external sunshade shading coefficient, and orientation correction factor, out of the 6 necessary variables that are needed to sufficiently interpret the thermal performance of the building envelope. $ENVLOAD_{simple}$ does not take consideration of the external wall's U value and the glazing's U value. This is also another reason why its errors are amplified.

3.5. Baseline value conversion

Previously, we have proven that OTTV can provide a simple and robust index to evaluate the thermal performance of a building envelope. The next question is how to convert the existing baseline value of ENVLOAD into the baseline value of OTTV. Fig. 5 shows the relationship between OTTV and ENVLOAD for the 1000 samples. The baseline value, as suggested in Taiwanese building envelope energy conservation regulation, of ENVLOAD in Kaohsiung is 115 kWh/m^2. Substituting this number into the regression line of ENVLOAD against OTTV in the diagram gives the corresponding OTTV = 38.4 W/m^2. This number value is the OTTV's baseline value corresponding to the currently active ENVLOAD's baseline value for the Kaohsiung region.

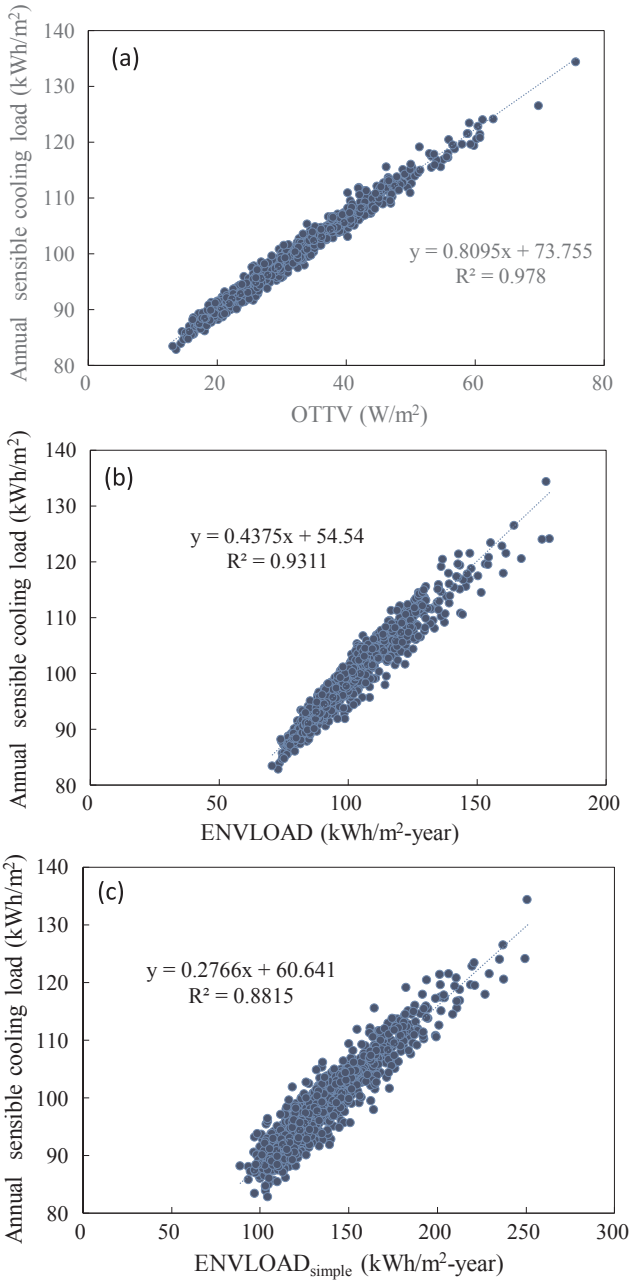

Fig. 4. Linear correlations of (a) OTTV, (b) ENVLOAD, and (c) $ENVLOAD_{simple}$, with annual sensible cooling loads.

Table 4
Comparative summary of the predictive performance of three models.

Prediction models	Statistics of predictive performance			
	R^2	MB	RMSE	IA
OTTV	0.98	0.88	1.14	0.93
ENVLOAD	0.93	1.55	2.01	0.87
$ENVLOAD_{simple}$	0.88	2.08	2.64	0.82

4. Results and discussions

4.1. Index adjustment and management in response to climate change

As the building cooling energy will vary with outdoor climate variation, the coefficient in the established building thermal performance

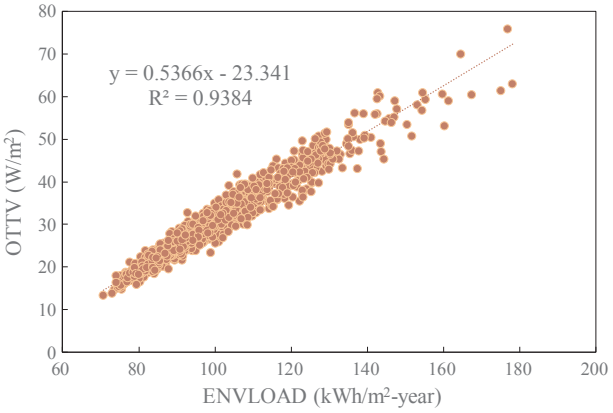

Fig. 5. Relationship between OTTV and ENVLOAD.

index (OTTV) should be altered periodically over times to correspond to the changing climate. To this end, the 1000 samples generated by Monte Carlo method were again used for EnergyPlus simulations to obtain annual sensible cooling loads yearly from 2005 to 2034. The frequency distribution of the 30,000 simulation results is plotted in Fig. 6 to illustrate the changes in the annual sensible cooling load over different time slice. Fig. 6 shows the frequency distribution curve pattern in the present era (from 2005 to 2019) is similar to that of the near-future eras (from 2020 to 2034). As expected, the distribution curve of the annual sensible cooling load in the near future shifted to the right of that in the present era, suggesting that the predicted annual sensible cooling load of perimeter zones will increase along with the increase in the level of future climate warming.

Fig. 7 shows the scatter plots of the annual average sensible cooling load (SCL) against OTTV of 1000 samples in the years between 2005 and 2019, as well as the years between 2020 and 2034. As shown in the plots, the linear regression equation for the years between 2020 and 2034 is similar to that of the years between 2005 and 2019; both have a very high R^2. From the policy point of view, it is important to mitigate the increase of the cooling load caused by climate warming by adjusting the specifications on the thermal performance regulation of the building envelope. In this paper, the adjustment logic is illustrated through the A, B, C, and D in Fig. 7. Assuming the envelope performance of a certain new building is designed in accordance with the currently active regulation baseline of OTTV = 38.4 W/m^2 (point A), the current annual sensible cooling load of perimeter zones will be 104.8 kWh/m^2 (point B). The annual sensible cooling load will naturally increase to 109.2 kWh/m^2 (point C) by 2020–2034 because of the warming climate. However, to let this new building maintain the same level of the annual cooling load between 2020 and 2034, as that between 2005 and 2019, the thermal performance regulation of the envelope must be strengthened to OTTV = 32.8 W/m^2 (point D). Specifically, the criteria of the OTTV for the envelope of a new building need to be reduced from the currently active 38.4 W/m^2 to 32.8 W/m^2 in 2020.

It is noteworthy that the regression line between 2020 and 2034 has higher values for the slopes and intercepts of the 2 linear regression lines in Fig. 7. The intercept for the years between 2020 and 2034 is 3.7 higher than that for the years between 2005 and 2019. This means that the annual sensible cooling load for the perimeter zones of the same building will increase by 3.7 kW/m^2 after 15 years under the influence of climate warming. An increase in slope means that the annual sensible cooling load in the years from 2020 to 2034 will become more sensitive along with the change in OTTV. Between 2005 and 2019, an increase of 1 W/m^2 in OTTV will cause an increase of 0.81 kWh/m^2 in the annual sensible cooling load; however, the increment in annual sensible cooling load will up to 0.83 kWh/m^2 between 2020 and 2034, which is equivalent to a 2.5% increase.

The SRC analysis is further used to check the causes of such changes. The variable with higher SRC value indicates there is more influential to the dependent variable, which is the annual sensible cooling load in this study. The results of the SRC analysis are shown in Table 5. It shows that the rankings of variables influencing the annual sensible cooling load from 2020 to 2034 are identical to those from 2005 to 2019. The first 3 most important variables are still SC_1, WWR, and SC_2. However, the SRC values of the two variables U_w and U_f in Table 5 are higher in the era from 2020 to 2034 than in the era from 2005 to 2019. This means that the future climate warming will cause the outdoor air temperature to increase, and the heat transfer due to temperature difference through the wall and the glass will also increase together, relatively lifting the importance of the U_w and U_f. In other words, the effect of lowering U_w and U_f in the era from 2020 to 2034 will be more significant in reducing the annual sensible cooling load than the effect in the era from 2015 to 2019. On the other hand, being marginalized by the increase in the influencing importance of U_f and U_w, which represent conduction heat by the temperature difference, the influencing importance of the solar radiation heat through fenestration is relatively lowered. Therefore, it is observed that the 4 parameters related to radiation heat transfer of open windows in Table 5, the SRC values of SC_1, SC_2, WWR, and CF between 2020 and 2034 are lower than the values in the years from 2005 to 2019.

Multivariate regression was used to construct the results of OTTV for the years from 2020 to 2034 as shown in Eq. (12). In comparison to the Eq. (11), it also shows that the regression coefficient of U_w increases from 5.1 to 5.9 and the regression coefficient of U_f increases from 1.6 to 2.3, which correspond to 16% and 44% increases, respectively. This means that the requirements on the thermal insulation performance of external walls and windows have to be stricter for the future climate. However, the regression coefficient value related to solar radiation heat gain remains almost unchanged; the variation margin is less than 1%.

$$OTTV_{i,near} = 5.9(1-WWR)\cdot U_w + 2.3WWR\cdot U_f + 107.3WWR\cdot SC\cdot CF \quad (12)$$

As demonstrated in the previous discussion, if the policy is desired to allow the annual sensible cooling load of newly built buildings in the era from 2020 to 2034 to refrain from the warming climate and to maintain at the same level as in the era from 2005 to 2019, in addition to lowering the OTTV baseline value there is still a need to alter the OTTV calculation equation, *i.e.* changing the regression coefficients of OTTV equation. After using the same logic as in Fig. 7, Fig. 8 shows that to maintain the same level of the annual sensible cooling load as that in the years from 2005 to 2019, the corresponding new OTTV baseline value occurs at 34.6 W/m^2.

4.2. Comprehensive comments on ENVLOAD and OTTV

By observing and comparing from the aforementioned ENVLOAD

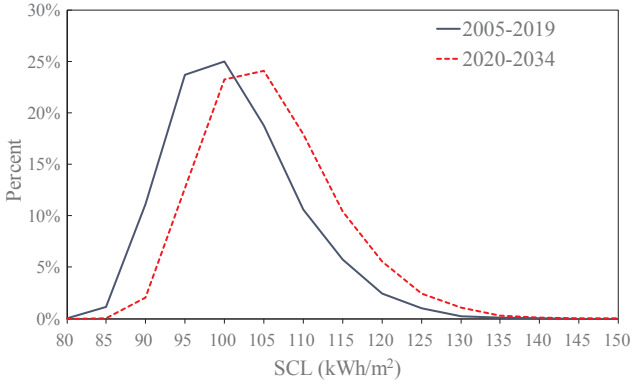

Fig. 6. Changing trends in different time periods.

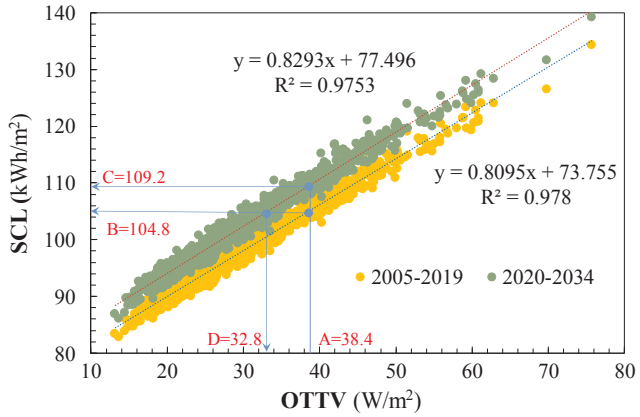

Fig. 7. Scatter plots of yearly average SCL against OTTV for different time periods.

Table 5
Comparison of SRC analysis results of different periods.

	SC_1	WWR	SC_2	U_W	CF	U_F
2005–2019	0.535	0.463	0.390	0.183	0.149	0.023
2020–2034	0.519	0.459	0.376	0.203	0.143	0.054

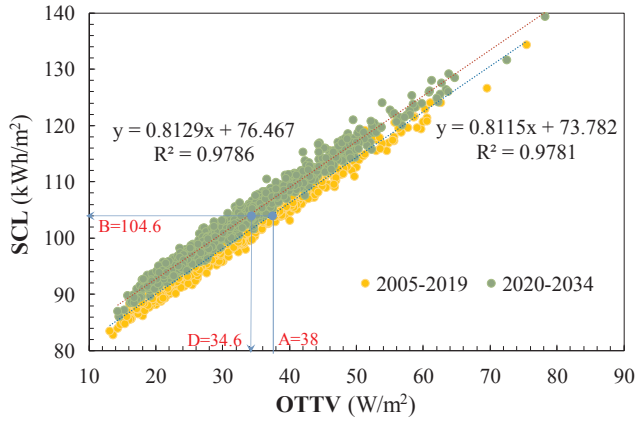

Fig. 8. Scatter plots of annual average SCL against OTTV for different time periods after adjustment.

and OTTV analysis results, the OTTV index evaluates the annual total heat transfer of a given building's unitary envelope area to reflect the energy-saving purpose in the building envelope design. The results are then easier to understand and to apply to the design of the building envelope. Meanwhile, ENVLOAD is aimed to calculate the actual annual cooling energy consumption of a building. The calculation of annual sensible cooling loads is conducted through the building's perimeter zone, resulting in its evaluation method being more complex. Although the $ENVLOAD_{simple}$ model had enormously simplified the evaluation processes of ENVLOAD, it has not taken consideration of the external wall U value and the glass U value, which is also the reason for its expanding prediction errors. In the face of climate change, adopting OTTV is more flexible and reasonable. It simplifies the setting of energy-saving targets to remind building designers of the desired goals and directions to be achieved by the building envelope design while being able to maintain the same sensible cooling load level as that in the past.

4.3. Application procedures of index alternation to adapt to the climate change

In this article, we take the new established OTTV of Taiwan as an example to demonstrate the alternation of OTTV to adapt to the changing climate. The general procedure that describes the alternation of any given building envelope regulation indices is summarized below. Note that the new OTTV equation for the future climate is established in the procedure (3) with its corresponding new criteria obtained in the procedure (5).

(1) Device a generic building model that is corresponding to the local building type, generating a series of building cases that utilize the Monte Carlo method to take building envelope design parameters as variables into consideration.
(2) Using existing meteorological datasets in performing the building energy simulations to obtain each case's annual sensible cooling load (SCL), and establish an OTTV regression line against the SCL of today.
(3) Using future meteorological datasets in performing the building energy simulations to obtain each case's SCL, and establish a future OTTV regression line against the SCL.
(4) Converting the baseline value (the criteria) of the index using the technique as is depicted in Fig. 8: Obtaining the corresponding SCL in the vertical axis with the existing/today's OTTV criteria by referring to the regression line developed from the procedure (2). The obtained SCL is the amount that a building has to be maintained in the future.
(5) By referring to the future OTTV regression line against the SCL developed in the procedure (3) and using the obtained SCL value found in the procedure (4), the new OTTV criteria value can be obtained in the horizontal axis.

5. Conclusions

As a building's energy use is intimately subjected to its ambient climate, it has been proven that the cooling energy use will be increase alongside with the future climate change, especially in the cooling dominated hot-and-humid Taiwan. To control and seek adaptation measures for buildings in facing with future climate from a policy perspective, effective building energy conservation regulation is considered a mean to regulate the building envelope design and to provide guidelines for architects in designing climate responsive buildings. The current ENVLOAD and $ENVLOAD_{simple}$ indices used in Taiwan are found insufficient to effectively reflect the climate change because of its complex form of calculation. Consequently, we addressed a need to develop a new index to cope with the future climate.

Therefore, a set of new OTTV index for the current (2005–2019) and the near future (2020–2034) of Taiwan was developed by analogizing to the equation form of OTTV in this study. Furthermore, we proposed a method of how to convert the baseline value of the existing building energy consumption index (ENVLOAD) to the newly developed OTTV. The new baseline value of the new index was suggested and the variation of the influences of building envelope parameters on the cooling energy use as impacted by the climate change was also discussed in this study. The research results reveal that not only the criteria of OTTV should be strengthened, the coefficients of the three major terms in OTTV equation should be altered as well for new buildings to confront with the future climate. The major contribution of this research is to let architects aware that the thermal performance requirement and the weighting of wall's U-value, glazing's U-value and its shading coefficient are different to those in the past and need to accommodate their building envelope design to respond to the changing climate. The following significant findings are reached:

- The newly developed OTTV was found more feasible and reasonable

to reflect the climate change and is capable of simplifying the calculation process, thus reduces the labor needed for evaluating the energy efficiency of a building as opposed to ENVLOAD. Therefore, it is advised and desirable to adopt the proposed OTTV index in the Taiwanese building energy conservation regulation as a countermeasure to future climate change.

- The baseline value of the newly developed OTTV is 38.4 W/m^2 corresponding to the current ENVLOAD criteria of Kaohsiung, *i.e.* 115 kWh/m^2.
- To maintain the annual sensible cooling load at the same level in 2020–2034 as in 2005–2019, the baseline value of OTTV should be further strengthened to 32.8 W/m^2 by the end of 2020 under the premise that the OTTV evaluation equation remains unaltered.
- However, as the contribution of each building envelope parameter to the annual cooling load may vary, the coefficients of the OTTV equation should regularly be updated over times to effectively reflect the warming climate. In this circumstance, the OTTV baseline value should be 34.6 W/m^2. The contributions of heat conduction related building envelope parameters (U_w and U_f) on the annual cooling load will gradually increase as climate change proceeds, suggesting a potential rising concern about the insulation property of the exterior building facade. Nevertheless, the solar radiation related parameters (*WWR*, SC_1, and SC_2) remain a dominating contribution to the annual sensible cooling load.

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